

## An Analysis of the Effect of the Building Envelope on Thermal Comfort using the EnergyPlus Program

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### Abstract

The scope of this study is to evaluate and compare the effect of exterior surface temperatures on the thermal comfort of a person. This study compares of thermal comfort predictions with the two types of approximate mean radiant temperature (MRT) calculations—"zone averaged" and "surface weighted"—using the EnergyPlus program. Due to the temperature differences between a standard MRT and individual surface temperatures, thermal comfort sensations will change according to the relative location of people within a space. The introduction of zone averaged and surface weighted MRT will be helpful in the accurate prediction of thermal comfort sensations without details information about the location of surfaces or people. This paper examines the three different case studies (residence, office, and gymnasium) using both the zone averaged and surface weighted MRT for three established thermal comfort models: the Fanger, the Pierce two-node, and the KSU two-node models. This paper shows that it is possible to obtain approximate differences in thermal comfort indices based on zone averaged and surface weighted MRT using the EnergyPlus program.

### Introduction

One of the main tasks of environment control system is to provide thermally comfortable indoor conditions for the occupants. For the purpose of evaluating the comfort level of people, many of mathematical models regarding thermal comfort have been developed during last forty years. From these, three thermal comfort prediction models by P.O. Fanger, J.B. Pierce Foundation, and the researchers at Kansas State University have been widely used. All three models are related to heat balance equations of human body and a thermal sensation scale. To predict the thermal sensation, the models use major environmental factors such as MAT (mean air temperature), MRT (mean radiant temperature), RH (relative humidity), air velocity, and a clothing insulation factor. The combination of these factors as well as activity level and work efficiency allows the calculation of thermal sensation prediction to be made. A brief overview of these three thermal comfort models is given below.

### Fanger Comfort Model

The model was first developed by P.O. Fanger at Kansas State University and Technical University of Denmark in 1967 and published in 1972. In this model, all major modes of energy losses from the human body are taken into account and the person is assumed to be at the steady state condition. The model was correlated from experimental data and results in a "predicted mean vote" (PMV) calculation that is based on the following equation:

$$PMV = (0.303e^{-0.036M} + 0.028)(H - L)$$

where:

H is the internal heat production rate of an occupant per unit area (= M – W), W/m<sup>2</sup>

L is all the modes of energy loss from body, W/m<sup>2</sup>

M is the metabolic rate per unit area, W/m<sup>2</sup>.

The resulting PMV value is evaluated on a seven-point scale where 0 represents relative comfort with the thermal surroundings, positive numbers indicate that an average person will feel warm, and negative numbers indicate cool to cold conditions.

### Pierce Two-Node Model

The John B. Pierce Foundation at Yale University began development of a mathematical thermal comfort model in 1970. The model divides the human body into two major compartments. One represents the internal core, and the other represents the skin. To determine the thermal sensations of human body, passive heat conduction from the core to the skin and the deviations of the core and the skin temperature from their set points are considered. The effects of shivering are also taken into account. The thermal sensation (TSENS) of an average person is calculated using one of the following equations:

$$TSENS = 0.4685(T_b - T_{b,c})$$

$$T_b < T_{b,c} \text{ in a cold environment}$$

$$TSENS = 4.7h_{ev}(T_b - T_{b,c})/(T_{b,h} - T_{b,c})$$

$$T_{b,c} \leq T_b \leq T_{b,h} \text{ in a warm environment}$$

$$TSENS = 4.7h_{ev} + 0.4685(T_b - T_{b,h}) \quad T_{b,h} < T_b \text{ in a hot environment}$$

where:

$T_b$  is the mean body temperature, °C

$T_{b,c}$  is the mean body temperature, lower limit for evaporative regulation zone, °C

$T_{b,h}$  is the mean body temperature, upper limit for evaporative regulation zone, °C

$\eta_{ev}$  is the evaporative efficiency.

The thermal sensation parameter obtained from these equations is compared to a scale that is similar to the one used for the Fanger model PMV calculation.

#### KSU Two-Node Model

This model was developed at Kansas State University and first published in 1974. The main improvements advanced by this model are the variation of thermal conductance between the core and the skin in cold environment and the variation of the skin wettedness in warm environment. The KSU two-node model results in a thermal sensation vote (TSV) that uses a similar scale as the Fanger model PMV and the Pierce model TSENS. TSV is evaluated using the following equations:

$$TSV = -1.46 \times e_{vc} + 3.75 \times e_{vc}^2 - 6.17 \times e_{vc}^3 \text{ in cold environment}$$

$$TSV = [5.0 - 6.56(RH - 0.5)] \times e_{wsw} \text{ in warm environment}$$

where:

$e_{vc}$ : Vasoconstriction factor

$e_{wsw}$ : Skin wettedness factor

RH: Relative humidity

#### EnergyPlus

EnergyPlus is a new building thermal performance simulation program that is due for its first official public release in April 2001. While it was originally intended to combine the best features of the BLAST (Building Loads Analysis and System Thermodynamics) and DOE-2 programs, the first release is expected to exceed this initial project goal in many ways. Developed using the heat balance based load calculation algorithm found in IBLAST (a research version of the BLAST program), EnergyPlus is capable of simulating the thermal conditions on a sub-hourly level and has integrated building, system, and plant sections that allow the effect of undersized systems or plants to be evaluated for a wide variety of spaces.

Two features of EnergyPlus make it ideal for this study. First, because it is based on a fundamental heat balance procedure where surface temperatures are evaluated as a part of the solution procedure, the radiative effect of surfaces on thermal comfort can be addressed. Without knowledge of the inside surface temperatures, thermal comfort calculations are not possible. Second, EnergyPlus has integrated the three thermal comfort models mentioned in the previous section into its simulation algorithm.

More information about the thermal comfort models and the EnergyPlus program are available in the literature. The next section describes work that is unique to the EnergyPlus program related to the evaluation of meant radiant temperatures (MRT) for thermal zones.

#### Zone Averaged and Surface Weighted MRT

Until now, most thermal comfort studies associated with full-featured thermal simulation programs have been hampered with two potential problems: either a lack of surface temperature information or a requirement that the user hand-calculate complex “angle factors” to define where a person is situated within a space. In EnergyPlus, new approach of MRT calculation has been introduced. While it is possible to obtain thermal comfort predictions for an “average” location through a standard MRT calculation, a “surface weighted” approach was developed to better account for the location of an individual without detailed specifications of the person’s location or the requirement to hand-calculate angle factors from the person to all of the surfaces within the space.

Because of difference between MRT for some average room location (referred to as a zone averaged MRT in this paper) and the temperature of a specific surface in a space, thermal comfort indices will change according to relative location of an individual within a space. When a person is “near” a particular surface, that surface will have a much greater effect on the person’s thermal comfort. This obvious fact is the purpose behind the “surface weighted” MRT calculation.

The zone averaged MRT is calculated using an area-emissivity weighting of all of the surfaces within a space using the following equation:

$$T_r = T_{r-avg} = \frac{\sum_{i=1}^n \epsilon_i A_i T_i}{\sum_{i=1}^n \epsilon_i A_i}$$

where:

$T_r$  is the mean radiant temperature, °C

$T_{r-avg}$  is the zone averaged mean radiant temperature, °C

$\epsilon_i$  is the emissivity of surface i

$A_i$  is the area of surface i, m<sup>2</sup>

$T_i$  is the temperature of surface i, °C

The zone averaged MRT does not include any other weighting for surfaces within a space other than area and thermal emissivity. The idea behind a surface weighted MRT is to allow the program user to specify a surface to which a person in the space will be closest. In the limit as the person gets closer and closer to that surface, the view factor from the person to that surface will approach 0.5. To approximate these conditions, the surface weighted MRT is thus the average temperature of the zone averaged MRT and the temperature of the surface to which a person is closest as shown in the following equation:

$$T_r = (T_{r-avg} + T_{surf}) / 2$$

where  $T_{surf}$  is the temperature of surface in °C. In reality, this does tend to over predict the effect of a particular surface because a person can never be “on” the surface. In addition, since the surface temperature in question is already part of the zone averaged MRT calculation, there is in effect some overlap of the surface temperature in the two MRT values. Nevertheless, the surface weighted MRT calculation is fairly straightforward and only requires a user to identify the surface the person is nearest to obtain a more realistic evaluation of thermal comfort.

To demonstrate both the zone averaged and surface weighted MRT calculations and their effect on thermal comfort predictions, several typical case studies were constructed. The purpose of these case studies is to demonstrate the two MRT calculations methods and also determine if there are any significant differences between the two. This is the focus of the next section.

### Case Studies

The three testing cases represent typical building types such as residence, office, and gymnasium. In all the cases, since the window surface is most affected by outdoor temperature and solar radiation, the windows on the south exterior walls are selected as testing surfaces for the thermal comfort prediction based on surface weighted MRT. The characteristics of each of the testing cases are described in the following subsections. A summary of the test case data is shown below in Table 1.

#### Residence

The residence example is intended to portray a typical bedroom in a single-family home. It assumes that two people will occupy the space at appropriate times throughout the day and that the only other internal heat gains come from two light bulbs. The room enclosure consists of two exterior walls (facing east and south) and two interior partitions. The south facing exterior wall has one single pane window that is identified as the surface temperature to be used in the calculation of the surface weighted MRT. During the winter months, it is assumed that the home is controlled to temperatures of 20°C from six to eight in the morning and from six to eleven in the evening and 16°C the remainder of the day. This is to account for a typical programmable thermostat and a reasonable occupancy schedule for two working adults.

#### Office

The office example is intended to portray a fairly standard office setting with one exterior wall (facing south) and three interior partitions. The example office room has typical lighting and equipment levels. The internal mass that is listed represents either a desk or a chair. The double pane window on the south wall is selected

as surface for surface weighted MRT calculation. In addition, the internal mass is also used as the key surface in the surface weighted MRT calculation to approximate an individual working at a desk. For heating season, during working hours, the office air temperature is controlled to 20°C; and otherwise, it is set at 15°C. During cooling season, the office is controlled to 23°C during working hours and allowed to float up to 30°C during night and weekend hours.

### Gymnasium

The gymnasium example is intended to portray a fairly typical American high school gymnasium with a main basketball court and bleachers for game spectators. Occupancy, lighting, and equipment levels were selected to simulate a Saturday evening schedule with several full-length games and a large crowd on hand. It was assumed that the games start in the early evening with preparation staff starting to arrive at approximately four in the afternoon. Post-game cleanup is assumed to end late in the evening. The double pane tinted window on the south exterior wall is selected as surface for calculating the surface weighted MRT. This is assumed to approximate a spectator seated near the window at the top of the bleachers. During the game, the maximum of three hundred spectators sit in the bleachers. During heating season, it is assumed that the space conditioning system maintains air temperatures of 20°C during the game hours and 15°C during all other times. During cooling season, the space is maintained at 23°C during games and allowed to reach 30°C at other times.

Building Type		Residential	Office	Gymnasium
Condition				
Geometry	Size of Space	6X6X2.5 (m)	3.6X3.6X2.5 (m)	21X21X8 (m)
	Wall Config.	2 exterior walls (South, West) 2 partitions	1 exterior wall (South) 3 partitions	3 exterior wall (South) 1 partitions
	Opening	Window: South wall 2(w) X 1.5(h) Single pane HW window	Window: South wall 3.4(w) X 1(h) Double pane tinted window	Windows: Each exterior wall 20(w) X 1(h) Double pane tinted window
	Internal Mass		2 (w) x 1 (h): Wood	
Test Environment	Location	Chanute AFB IL	Chanute AFB IL	Chanute AFB IL
	Design days	Winter: 1/21 Summer: 7/21	Winter: 1/21 Summer: 7/21	Winter: 1/21 Summer: 7/21
Scheduled Loads	No. Of People	2 Occupants (Activity Level: 0.13kW)	1 Occupant (Activity Level: 0.13kW)	300 Spectators (Activity Level: 0.13kW)
	Lights	0.12kW (Peak)	1 W/ft <sup>2</sup>	1.5 W/ft <sup>2</sup>
	Equipments		1 W/ft <sup>2</sup>	

**Table 1.** Test conditions of the three cases.

### Results

The results of the three case studies are shown in Figures 1 through 12. These figures show that there can be significant differences between the thermal comfort predictions based on zone averaged MRT and those based on surface weighted MRT. In all cases, it is fairly easy to follow the trends between the zone averaged and surface weighted MRT thermal comfort calculations by tracking the variation of mean air temperature, mean radiant temperature, and the surface temperature being considered. The most notable trend is that the differences between the zone averaged and surface weighted results are significantly greater in winter than in summer for all cases. This results from the greater temperature differences between zone averaged MRTs and the temperatures of the window surfaces in winter. The results also show the noticeable pattern of thermal sensation indices during the summer. In summer, at the time of around eight in the morning, the thermal sensation based on the surface weighted MRT goes higher than that based on the zone averaged MRT until around seven in the evening, due to the solar absorption by the window surface. The influence of the solar absorption to thermal sensation becomes lesser in winter because the surface temperature of the window is still significantly colder than the other surfaces. In the office spaces, it is

important to note that there was very little difference between the thermal comfort indices calculated for the zone averaged MRT and the surface weighted MRT based on the internal mass element. This indicates that there are some cases where the use of a zone averaged MRT is reasonable and that exterior surface effects might not be as pronounced as anticipated.

It should be noted that in all cases run for this study, a clothing insulation value of 1.0 clo was used. Moreover, the thermal comfort studies did not take into account air stratification, solar radiation absorbed directly by occupants, and the use of blankets in the residence. All of these factors may influence the final results some, but the trends seen in Figures 1 through 6 are expected to hold even when considering some of these other effects.

#### Residence

(insert Figure 1 here)

Figure 1. Temperature Profile and Thermal Sensation Predictions (Residential Space in Winter).

(insert Figure 2 here)

Figure 2. Temperature Profile and Thermal Sensation Predictions (Residential Space in Summer).

#### Gymnasium

(insert Figure 3 here)

Figure 3. Temperature Profile and Thermal Sensation Predictions (Gymnasium in Winter).

(insert Figure 4 here)

Figure 4. Temperature Profile and Thermal Sensation Predictions (Gymnasium in Summer).

#### Office

(insert Figure 5 here)

Figure 5. Temperature Profile and Thermal Sensation Predictions (Office Space in Winter).

(insert Figure 6 here)

Figure 6. Temperature Profile and Thermal Sensation Predictions (Office Space in Summer).

Throughout the study and evaluation of thermal comfort with EnergyPlus, an interesting effect was noticed. Unlike other two models, the KSU two-node has a discontinuity in thermal sensation prediction due to its different prediction of heat conduction between the core and the skin in colder and warmer thermal environments. The use of two different equations for the different environmental conditions caused the resulting TSV predictions to have large discontinuities despite the fact that the conditions within the zone had not changed significantly. Because of this discontinuity, the results for the KSU model are not included in this paper. Modification of the KSU model to solve the problems this discontinuity presents is an area that will require further research.

#### Conclusion

In conclusion, this paper shows the value of thermal comfort calculations and the need for accurate representations of where people are located within a space. Using the concepts of zone averaged and surface weighted mean radiant temperatures, it is possible to determine the effect that a building's skin might have on the thermal comfort of an occupant of the building. Most of the cases investigated in the above sections show that the placement of individuals is much less critical in the summer when the difference between air and surface temperatures are expected to be smaller than in winter when difference can be significantly larger. The results also demonstrate the usefulness of a program such as EnergyPlus in designing buildings from both an energy and a comfort perspective. While future thermal comfort research with the EnergyPlus program is expected to center around the discontinuities noted in some cases with the KSU two-node model, the first release of EnergyPlus will allow architects and engineers to estimate the effect of a building's skin on thermal comfort using three established models and two methods for determining mean radiant temperature.

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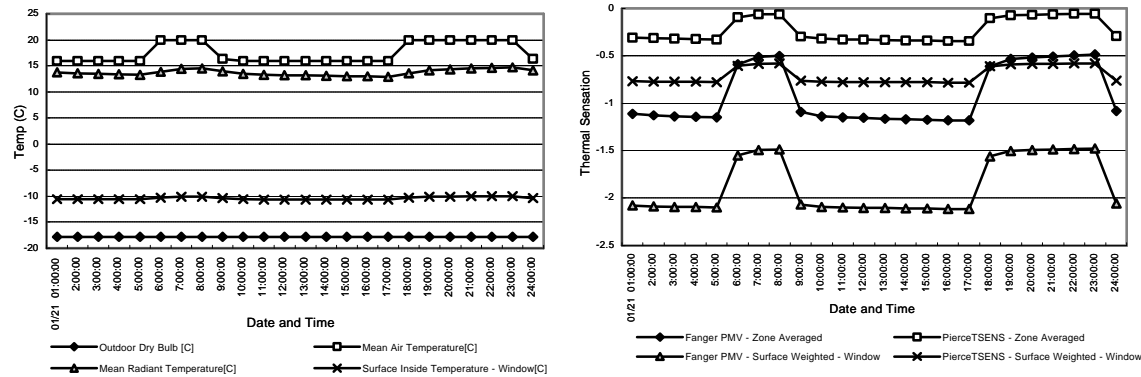


Figure 1. Temperature Profile and Thermal Sensation Predictions (Residential Space in Winter).

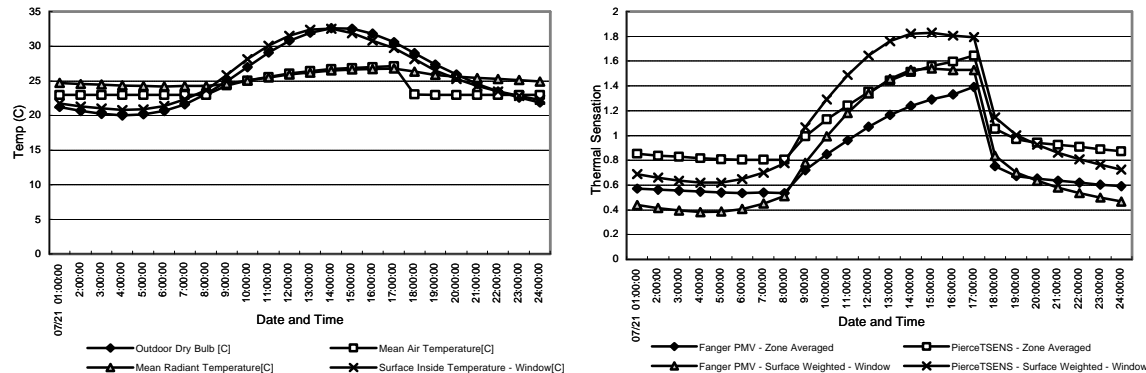


Figure 2. Temperature Profile and Thermal Sensation Predictions (Residential Space in Summer).

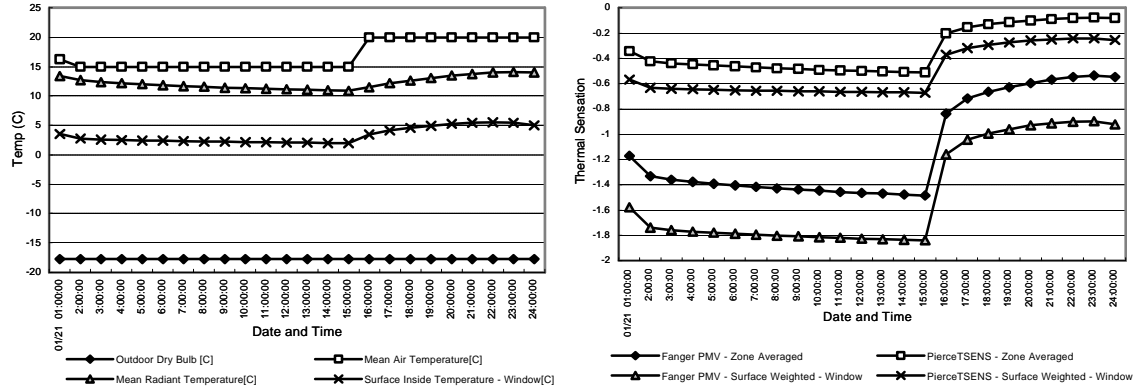


Figure 3. Temperature Profile and Thermal Sensation Predictions (Gymnasium in Winter).

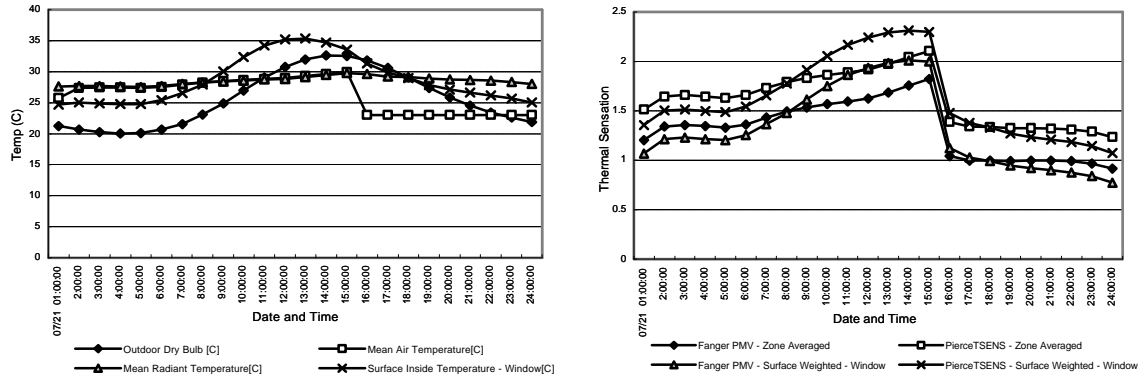


Figure 4. Temperature Profile and Thermal Sensation Predictions (Gymnasium in Summer).

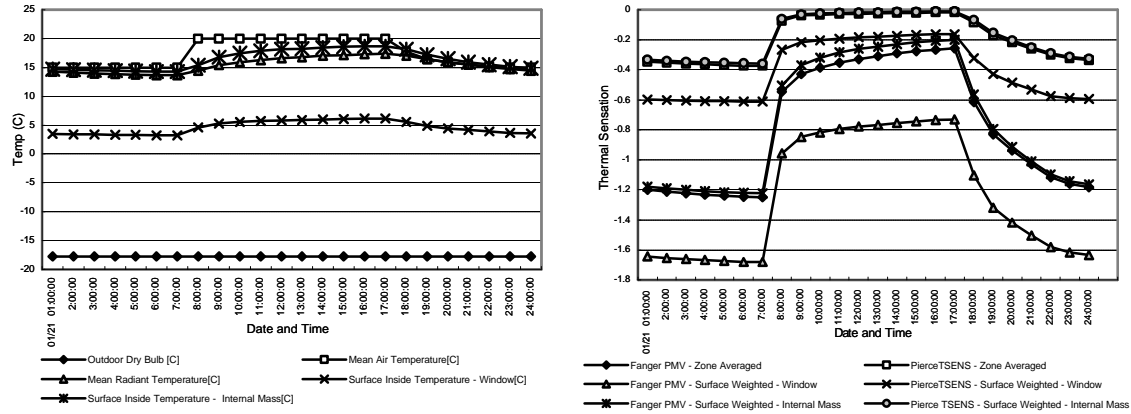


Figure 5. Temperature Profile and Thermal Sensation Predictions (Office Space in Winter).

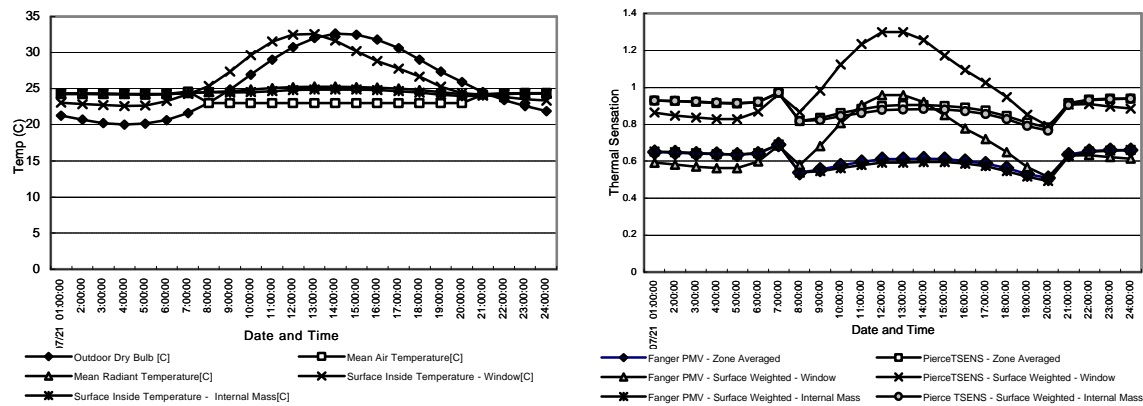


Figure 6. Temperature Profile and Thermal Sensation Predictions (Office Space in Summer).